Analysis of Wake Waves of Maersk Idaho on the Houston Ship Channel

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Summary

Based on the existing theories of ship-wave generation and wave propagation in finite water depth, we analyzed the wake properties of Maersk Idaho advancing on the Houston ship channel. We found that the maximum possible height of Idaho-generated-waves in the water with a perpendicular distance of about 926 m (i.e. 0.5 nautical miles) from the ship track line could not be more than 0.67 m (i.e. 2.2 ft).

Known Parameters

Topography: Houston ship channel has a width of 1000 ft, consisting of deep ship channel of a width of 500 ft (with depth of 45 ft) in the middle and shallow barge channels (of depth 12 to 20 feet) at two sides. Outside the channel, the water depth reduces to about 7 ft.

Maersk Idaho:
Length Overall = 292 m
LBP=277m
Breadth =32 m
Mean draft =11.5 m
Displacement = 51952 Tonnes
Navigation peed = 15 knots

Wake Size and Wave Features

Propagation of ship generated waves in finite water depth is strongly influenced by the depth-dependent Froude number, $F_d = \frac{U}{\sqrt{gd}}$, where U is the speed of ship, g is the gravitational acceleration ($g = 9.81$ m/s^2), and d is the water depth.

From classical ship wave theory (Havelock 1908), the largest waves are generally along the so-called cusp locus line at an angle α with respect to the track line sweeping aft from the bow of ship. Along the cusp locus and for $F_d < 1.00$ (referred to as the "subcritical flow"), the diverging waves and transverse waves meet at the maxima for both sets of waves and the largest waves are generally found there. The angle α is equal to 19.5 degrees for F_d less than 0.6 and increases to 90 degrees as F_d increases to 1.0, as shown in Fig. 1a.

For F_d ≥1.00 (referred to as "supercritical flow"), the transverse waves and cease to exist, and there is no cusp locus line. The largest waves are along the wake half angle that decreases from 90 degrees to about 20 degrees as F_d increases from 1.0 to about 3.0, and continuously decreases to zero as F_d further increases, as shown in Fig. 1b.

Inside the ship channel, the water depth is d_1 =13.72 m (45 feet). With the ship speed $U = 7.65$ m/s (15 knots), we have Froude number $F_{d1} = 0.66$. The cusp locus angle α_1 = 20 degrees from Fig. 1a. In the shallow water region outside the channel, we assume a constant depth of d_2 =2.13 m (7 feet). The corresponding Froude number F_{d2} =1.67. The wake half angle is about $\alpha_2 = 38$ degrees from Fig. 1b. From the deep ship channel to the edge of the entire channel, the water depth decreases from 13.72 m to 2.13 m. In this narrow strip region, the wake half angle increases from 20 degrees to 38 degrees. Fig. 2 displays a sketch diagram of the wake size of Maersk Idaho (at 15 knots). The interest here is not in the waves in the channel, but the waves outside the channel.

Wave Height Variation in the Wake

Inside the wake in the channel, significant waves can exist. The largest waves generally are located near the cusp locus line BP, as sketched in Fig. 2, where both diverging waves and transverse waves exist. Outside the cusp line, the ship waves are much smaller in amplitude. From classical theory (Havelock 1908, Ursell 1960), it is well known that for subcritical flow, the wave height on the cusp line varies inversely with cube root of the perpendicular distance from the track line (i.e. the *y*-coordinate in Fig. 2), while the wave height inside the wake varies inversely with square root of *y*. These features of wave height were verified in experimental observations (Kriebel et al. 2003).

In the shallow water region outside the channel, the corresponding Froude number F_{d2} =1.67 so the wake is in supercritical flow. Only diverging waves exist while transverse waves and the cusp line do not exist. The largest waves occur near the wake half angle line PQ, as shown in Fig. 2. For supercritical flow, it is known from existing theory (Havelock 1908; Pethiyagoda et al. 2015) that the wave height in the wake varies inversely with the square root of the perpendicular distance from the track line (i.e. the *y*-coordinate in Fig. 2). The main focus of this study is on the large diverging waves along the half wake angle line PQ. From this theory, the wave heights at locations P and Q are related by the relation:

$$\frac{H_p}{H_q} = \left(\frac{y_p}{y_q}\right)^{-\frac{1}{2}} \qquad (1)$$

where H_p and H_q represent the wave heights at P and Q, respectively, and y_p and y_q are the perpendicular distances from the track line of points P and Q, respectively. The equation (1) can also be written in the alternative form: $H_p^2 y_p = H_q^2 y_q$ which is consistent with the principle of conservation of wave energy.

The wave height H_q at point Q, far away from the ship, can be determined from equation (1) in terms of the wave height H_p at point P, which is located at the edge of the channel and is much

closer to the ship than point Q. The wave height H_q at point Q is clearly smaller than H_p at point P as the distance y_q is larger than y_p.

By the use of direct numerical simulation of wave generation by Maersk Idaho advancing at 15 knots, we obtained a prediction of the generated diverging and transverse wave field in the channel near the ship. The modeling is based on the formulation of incompressible fluid dynamics for ship wave generation in finite water with varying depth. The typical wave height in the channel is obtained to be 0.6 m (2.0 feet). The generated waves in the water outside the channel and far away from the ship (e.g. point Q in Fig. 2) could not be obtained by direct numerical simulation due to the requirement of huge computational costs. Despite this, we could estimate the wave height at point Q using equation (1) with the computed wave height $H_p = 0.6$ m at point P. Since point P is located at the edge of the channel, we have y_p=152 m (i.e. 500 ft, half channel width). For the downstream point Q located at $y_q = 926$ m (i.e. 0.5 nautical miles from the track line), we obtained $H_q = 0.24$ m (about 0.8 feet). Due to simplifications in modeling and the resolution limited by available computing resources, the predicted wave height at point Q could be underestimated. However, since the wave height is ultimately limited by the water depth, as a conservative approach, we can estimate the upbound of the wave height for wave propagation in finite water depth using the wave-breaking criterion, regardless of how accurate the wave generation of Maersk Idaho is computed.

Estimate of Maximum Possible Height of Maersk Idaho Generated Waves

From the theory of wave propagation in finite depth, it is generally known from the so-called McCowan's criterion (Hardisty and Laver 1989) that a wave cannot maintain its form and will break once the wave height reaches the maximum value of $d/1.3$. When wave breaking occurs, the wave's energy is dissipated, and its height is largely reduced in the propagation. The wave breaking criterion also indicates that the maximum wave height that a non-breaking wave can reach is $(H)_{max} \leq d/1.3$, where d is the local water depth.

Using the wave-breaking criterion, we can estimate the maximum wave height that can possibly exist in the shallow water wake of Maersk Idaho. We have the maximum possible height of a non-breaking wave at point P (at the edge of the channel)

$$\left(H_p\right)_{max} \leq \frac{d}{1.3} = 1.64 \text{ m (i.e. 5.4 feet).}$$

From equation (1), the maximum possible wave height at point Q (at 0.5 nautical miles from the track line) is obtained to be:

$$\left(H_q\right)_{max} = 0.41 \left(H_p\right)_{max} \leq 0.67 \text{ m (i.e. 2.2 feet).}$$

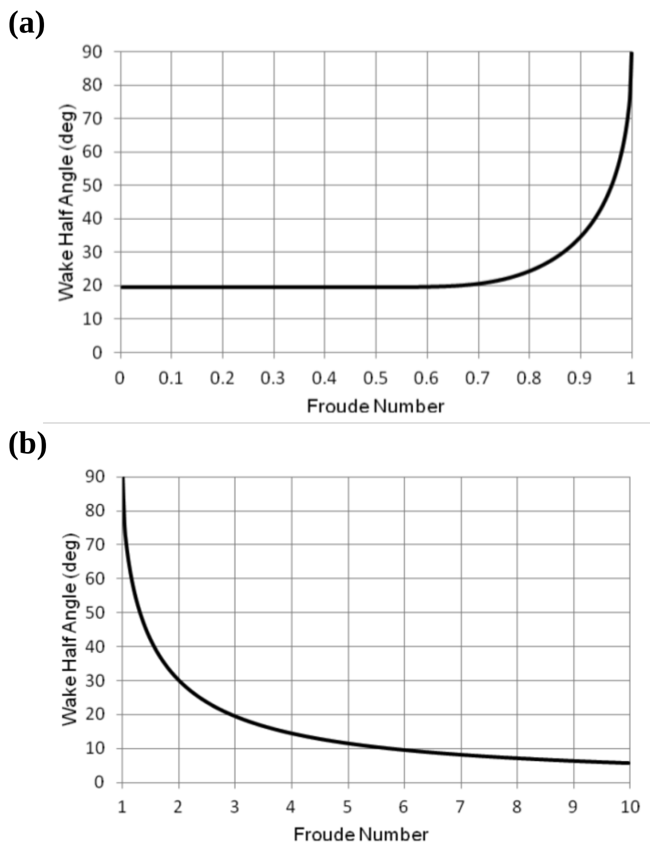

Figure 1. Wake half angle as a function of Froude number F_d (Tunaley 2014).

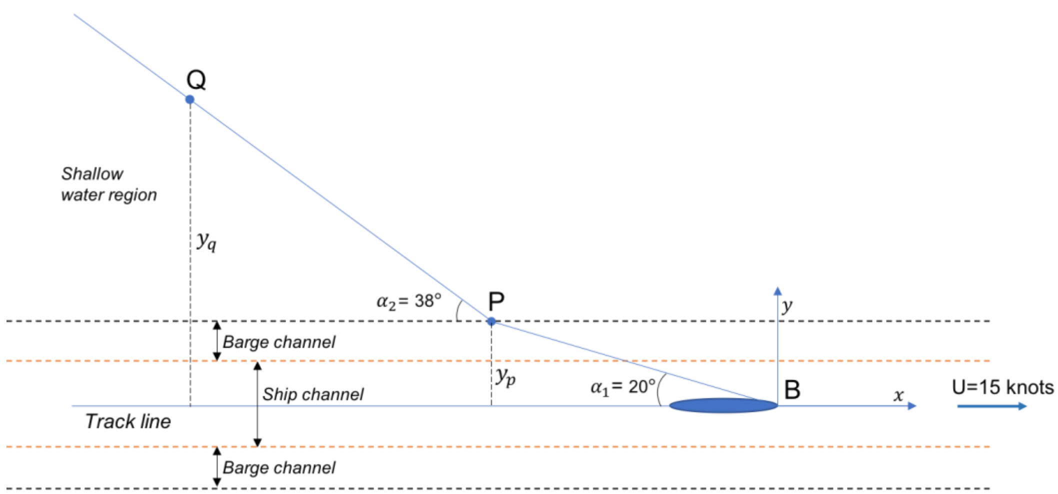

Figure 2: A schematic diagram of the half wake of Maersk Idaho advancing on the Houston ship channel. The wake is symmetric about the track line. y_p=152 m (500 ft) and y_q = 926 m (0.5 nautical miles). Note that the coordinates y_p and y_q are not drawn to scale.

Drs. Dick K.P. Yue and Yuming Liu are compensated at the rates of $750/hour and $300/hour, respectively.

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Visiting Professor, Stanford University, 1996-1997.
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Japanese Government Foreign Specialist Research Award, 1987.
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94. "Air entrainment and multiphase turbulence in the bubbly wake of a transom stern," *International Shipbuilding Progress*, **60**:375-401 (2013) (with Hendrickson, K. et al).
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96. "Physical limits on cellular directional mechanosensing," *Physical Review E*, 87**, 5** (2013) (with Bouffanais, R. & Sun, J.).
97. "SPH for incompressible free-surface flows. Part I: Error analysis of the basic assumptions," *Computers & Fluids*, **86**: 611-624 (2013) (with Kiara, A. & Hendrickson, K.).
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99. "Monte Carlo radiative transfer simulation for the near ocean surface high-resolution downwelling irradiance statistics", *Journal of Optical Engineering,* **53** (5) (2014) (with Xu, Z.).
100. "Persistent cellular motion control and trapping using mechanotactic signaling," *PLOS ONE,* **9(9)** (2014) (with Zhu, X. & Bouffanais, R.).
101. "Directional mechanosensing of amoeboid cells," *Biophysics Journal,* **106 (**176a-177a) (2014) (with Zhu, X. & Bouffanais, R.).
102. "Direct numerical investigation of turbulence of capillary waves," *Physical Review Letters*, **113** (2014) (with Pan, Y.)

103. "Interplay between motility and cell-substratum adhesion in amoeboid cells," *Biomicrofluidics*, **9(5)**, 054112 (2015) (with Zhu, X. & Bouffanais, R.)
104. "Analytical solution of beam spread function for ocean light radiative transfer," *Optics Express*, **23,** 17966-17978 (2015) (with Xu, Z.)
105. "Efficiency of Fish Propulsion," *Bioinspiration & Biomimetics*, **10**, (2015) (with Maertens, A. & Triantafyllou, M.S.)
106. "Decaying capillary wave turbulence under broad-scale," *Journal of Fluid Mechanics*, **780**: 357-392 (2015) (with Pan, Y.).
107. "Three-dimensional effects on flag flapping dynamics," *Journal of Fluid Mechanics*, **783**: 103-136 (2015) (with Banerjee, S., Connell, B.).
108. "Interplay between motility and cell-substratum adhesion in amoeboid cells," *Biomicrofluidics*, **9**, 054112 (2015) (with Zhu, X. & Bouffanais, R.)
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115. "Nonlinear phase-resolved reconstruction of irregular water waves," *Journal of Fluid Mechanics*, **838**: 544-572 (2018) (with Qi, Y., et al).
116. "Modeling variation coefficient of wave-induced underwater irradiance for clear ocean and its application to find the optimal detector size," *Applied Optics*, **57**(17), 4785-4794 (2018) (with Xu, Z.).
117. "On high-order perturbation expansion for the study of long-short wave interactions," *Journal of Fluid Mechanics*, **846**: 902-915 (2018) (with Pan, Y. & Liu, Y.).
118. "A space-time integral minimization method for the reconstruction of velocity fields from measured scalar fields," *Journal of Fluid Mechanics*, **854**: 348-366 (2018) (with Gillissen, J. et al).
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123. "Wake behind a three-dimensional dry transom stern. Part 1: Flow structure and large-scale air entrainment," *Journal of Fluid Mechanics*, **875**: 854-883 (cover article) (2019) (with Hendrickson, K. et al).

124. "Wake behind a three-dimensional dry transom stern. Part 2: Analysis and modeling of incompressible highly-variable density turbulence," *Journal of Fluid Mechanics*, **875**: 884-913 (2019) (with Hendrickson, K.).
125. "Data assimilation method to de-noise and de-filter particle image velocimetry data," *Journal of Fluid Mechanics*, **877**: 196-213 (2019) (with Gillissen, J. & Bouffanais, R.).
126. "Numerical Investigation of Shear-Flow Free-surface Turbulence and Air Entrainment at Large Froude and Weber Numbers," *Journal of Fluid Mechanics*, **880**: 209-238 (2019) (with Yu, X. et al).
127. "Energetics of optimal undulatory swimming organisms," *PLOS Computational Biology*, **15**(10): e1007387. https://doi.org/10.1371/journal.pcbi.1007387 (2019) (with Tokić, G.).
128. "Scale separation and dependence of entrainment bubble size distribution in free-surface turbulence," *Journal of Fluid Mechanics ─ Rapids*, **885:** R2. (2019) (with Yu, X. & Hendrickson, K.).
129. "Informed Component Label Algorithm for Robust Identification of Connected Components with Volume-of-Fluid Method," *Computers & Fluids*, **197** (2020) (with Hendrickson, K. & Weymouth, D.).

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BOOK PUBLICATION

1. "Theory and Applications of Ocean Surface Waves," World Scientific, 2 Volumes. (2018) (with Mei, C.C., Stiassnie, M.)

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1. "Oblique sub- and super-harmonic Bragg resonance of surface waves by bottom ripples," *Journal of Fluid Mechanics*, **643**: 437-447 (2010) (with Alam, R. & Liu, Y.).
2. "Conservative Volume-of-Fluid Method for Free-Surface Simulations on Cartesian Grids," *Journal of Computational Physics*, **229**: 2853-2865 (2010). (with Weymouth, G.).
3. "Hydrodynamics of cell-cell mechanical signaling in the initial stages of aggregation," *Physical Review E*, **81:** 041920-1:16 (2010). (with Bouffanais, R.). Also selected to appear in: *Virtual Journal of Nanoscale Science & Technology*, **21** (19) (2010); and *Virtual Journal of Biological Physics Research*, **19**, (9) (2010).
4. "Hydrodynamic object recognition using pressure sensing," *Proceedings of the Royal Society London **A***, **467**: 19-38 (2011) (with Bouffanais, R. & Weymouth, G.).
5. "Transport of passive scalar in turbulent shear flow under a clean or surfactant-contaminated free surface," *Journal of Fluid Mechanics*, **670**: 527-557 (2011) (with Khakpour, H.R. & Shen, L.).
6. "Resonant wave signature of an oscillating and translating disturbance in a two-layer density stratified fluid," *Journal of Fluid Mechanics*, **675**: 477–494 (2011) (with Alam, R. & Liu, Y.).
7. "Boundary Data Immersion Method for Cartesian-Grid Simulations of Fluid-Body Interaction Problems," *Journal of Computational Physics*, **230**: 6233-6247 (2011) (with Weymouth, G.).
8. "A model for the probability density function of downwelling irradiance under ocean waves," *Optics Express*, **19**: 17528–17538 (2011). Also, *Virtual Journal for Biomedical Optics (VJBO)*, **6** (9) (2011) (with Shen, M. & Xu, Z.)
9. "Attenuation of short surface waves by the sea floor via nonlinear sub-harmonic interaction," *Journal of Fluid Mechanics*, **689**: 529–540 (2011) (with Alam, R. & Liu, Y.).
10. "Recent advances in the study of optical variability in the near-surface and upper ocean," *Journal of Geophysical Research, Oceans*, **116**: (2011) (with Dickey, T. et al).
11. "Patterns and statistics of in-water polarization under conditions of linear and nonlinear ocean surface waves," *Journal of Geophysical Research, Oceans*, **116**: (2011) (with Xu, Z. et al).
12. "Radiative transfer in ocean turbulence and its effect on underwater light field," *Journal of Geophysical Research, Oceans*, **116**: (2011) (with Xu, Z. et al).
13. "Boundary-element method for the prediction of performance of flapping foils with leading edge separation," *Journal of Fluid Mechanics*, **698**: 446–467 (2012) (with Pan, Y. et al).
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18. "SPH for incompressible free-surface flows. Part I: Error analysis of the basic assumptions," *Computers & Fluids*, **86**: 611-624 (2013) (with Kiara, A. & Hendrickson, K.).

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40. “Hydrodynamics of periodic wave energy converter arrays,” *Journal of Fluid Mechanics*, **862**: 34-74 (2019) (with Tokić, G.).

41. "Structures and Mechanisms of Air-Entraining Quasi-Steady Breaking Ship Waves," *Journal of Ship Research*, **63(2)**: (2019) (with Hendrickson, K.).
42. "From solar cells to ocean buoys: Wide-bandwidth limits to absorption by metaparticle arrays," *Physical Review Applied*, **11**: 304033 (2019) (with Benzaouia, B. et al).
43. "A fast multi-layer boundary element method for direct numerical simulation of sound propagation in shallow water environments," *Journal of Computational Physics*, **392**: 694-712 (2019) (with Li, C. et al).
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47. "Numerical Investigation of Shear-Flow Free-surface Turbulence and Air Entrainment at Large Froude and Weber Numbers," *Journal of Fluid Mechanics*, **880**: 209-238 (2019) (with Yu, X. et al).
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List of D.K.P. Yue's Prior Testimony in Last Five Years

The M/V Dixie Vengeance case
Deposition date: January 18, 2019

CURRICULUM VITAE

YUMING LIU

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EDUCATION

Ph.D. in Hydrodynamics, M.I.T., **1994**. Theoretical and computational wave hydrodynamics.

S.M. in Coastal Engineering, University of Florida, 1988. Estuary dynamics and sediment transport.

S.B. in Civil Engineering, Hohai University, China, 1985. Structural mechanics and coastal engineering.

RESEARCH EXPERIENCE

Senior Research Scientist (5/2017 –present)
Principal Research Scientist and Senior Lecturer (7/99 – 4/2017); Research Scientist (1/96 -- 6/99)
Department of Mechanical Engineering, MIT

(1) Design and analysis of ships and marine structures: Development and application of analysis and simulation tools for the design of advanced vehicles and offshore structures including modeling and computation of three-dimensional breaking waves, impact loads due to steep waves and water entry, fully-nonlinear hydrodynamic loads on large floating bodies, and large-amplitude motions of ships and aquaculture fishing cages in rough seas.

(2) Prediction of ocean environments: Development and application of a new generation of tools for prediction of large-scale nonlinear ocean surface wave-field evolution including interactions with currents, wind, and bottom topography. Development of advanced algorithms and computational tools for deterministic reconstruction and (short-time) forecasting of realistic ocean waves using phase-resolved wave simulations and sensed (point/whole-area) surface wave data. Modeling and prediction of resonant interactions of surface and internal waves with objects and sandy/muddy ocean bottom.

(3) Hydrodynamics of multiphase flow in channels/pipelines: Development and application of physics-based DNS/LES simulation capabilities for understanding and prediction of the hydrodynamics and regime transition of violent multiphase (gas/liquid/solid) flows in channels and pipes.

(4) Ocean and musical acoustics: Development of highly efficient computational tools for direct computation and prediction of underwater acoustics in complex nearshore ocean environments. Investigation of fundamental music acoustics of stringed instruments.

Postdoctoral associate (6/94 -- 12/95)
Department of Ocean Engineering, MIT

Prediction and analysis of surface-wave patterns above near-surface bodies for the detection of underwater objects using remote sensing; and stability analysis of a helical vortex filament under a free surface for the design of advanced propellers and marine structures.

CONSULTANT TO

Advanced Marine Technology (AMT), Cambridge, MA.
ChevronTexaco Corporation, Houston, TX.
ExxonMobil Upstream Research Company, Houston, TX.
ConocoPhlipps Inc., Houston, TX

SELECT RELEVANT PUBLICATIONS IN REFEREED JOURNALS

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2. Miao, S., Hendrickson, K. & Liu, Y. 2019 Slug generation processes in co-current turbulent gas/laminar-liquid flows in horizontal channels. *Journal of Fluid Mechanics* **860**. pp. 224-257
3. Li, C, Campbell, B, Liu, Y. & Yue, D.K.P. 2019 A fast multi-layer boundary element method for direct numerical simulation of sound propagation in shallow water environments. *Journal of Computational Physics* **392**, pp 694-712.
4. Shen, M. & Liu, Y. 2019 Subharmonic resonant interaction of gravity-capillary progressive axially symmetric wave with radial cross-wave. *Journal of Fluid Mechanics* **869**, pp. 439–467.
5. Peng, J., Tao, A., Liu, Y., Zheng, J., Zhang, J. and Wang, R. 2019 A laboratory study of class III Bragg resonance of gravity surface waves by periodic beds. *Physics of Fluids* **31**.
6. Li, C. & Liu, Y. 2018 On the weakly nonlinear seakeeping solution near the critical frequency. *Journal of Fluid Mechanics* **846**, pp. 999 -1022
7. Pan, Y., Liu, Y. and Yue, D.K.P. 2018 On high-order perturbation expansion for the study of longshort wave interactions. *Journal of Fluid Mechanics* **846**, pp. 902-915.
8. Qi, Y., Wu, G., Liu, Y., Kim, M.-H. and Yue, D. K.P. 2018 Nonlinear phase-resolved reconstruction of irregular water waves. *Journal of Fluid Mechanics* **838**, pp 544-572.
9. Qi, Y., Wu, G., Liu, Y. and Yue, D.K.P. 2018 Predictable zone for phase-resolved reconstruction and forecast of irregular waves. *Wave Motion* **77**, pp 195-213.
10. Miao, S., Hendrickson, K. & Liu, Y. 2017 Computation of three-dimensional multiphase flow dynamics by Fully-Coupled Immersed Flow (FCIF) solver. *Journal of Computational Physics* 350: 97-116. https://doi.org/10.1016/j.jcp.2017.08.042
11. Shen, M. & Liu, Y. 2017 Current effects on global motions of a floating platform in waves. *Ocean Systems Engineering*, Vol. 7, No. 2, pp 121-141. DOI : 10.12989/ose.2017.7.2.121
12. Zhang, W., Liu, Y., Ratilal, P., Cho, B. & Makris, N.C. 2017 Active nonlinear acoustic sensing of an object with sum or difference frequency fields. *Remote Sens.*, *9*(9), 954; doi: 10.3390/rs9090954
13. Campbell, B. & Liu, Y 2016 Nonlinear coupling of interfacial instabilities with resonant wave interactions in horizontal two-fluid plane Couette/Poiseuille flows: Numerical and Physical Observations. *Journal of Fluid Mechanics*, **809**: 438-479.
14. Campbell, B. & Liu, Y 2016 A nonlinear flow-transition criterion for the onset of slugging in horizontal channels and pipes. *Physics of Fluids*, **28**: 082103.
15. Miao, S. & Liu, Y. 2015 Wave pattern in the wake of an arbitrary moving surface pressure disturbance. *Physics of Fluids*, **27**: 122102.
16. Nia, H.T., Jain, A.D., Liu, Y., Alam, M.-R., Barnas, R. & Makris, N.C. 2015 The evolution of air resonance power efficiency in the violin and its ancestors. *Proc. R. Soc. A* **471**: 20140905.
17. Campbell, B. & Liu, Y. 2014 Sub-harmonic resonant wave interactions in the presence of a linear interfacial instability. *Physics of Fluids*, **26**: 082107.

18. Campbell, B. & Liu, Y. 2013 Nonlinear resonant interaction of interfacial waves in horizontal stratified channel flows. *Journal of Fluid Mechanics*, **717:** 612-642.

19. Xiao, W., Liu. Y., Wu, G. & Yue, D.K.P. 2013 Rogue wave occurrence and dynamics by direct simulations of nonlinear wavefield evolution. *Journal of Fluid Mechanics*, **720:** 357-392.

20. Dickey, T. …Liu, Y., … 2012 Introduction to special section on recent advances in the study of optical variability in the near-surface and upper ocean. *Journal of Geophysical Research*, Vol 117, C00H20.

21. Yan, H. & Liu, Y. 2011a An efficient high-order boundary element method for nonlinear wave-wave and wave-body interactions. *Journal of Computational Physics* **230**, pp. 402-424.

22. Yan, H. & Liu, Y. 2011b Nonlinear computation of water impact of axisymmetric bodies. *Journal of Ship Research*, Vol. 55, No. 1, pp. 29-44.

23. Alam, M.-R., Liu, Y. and Yue, D.K.P. 2011a Nonlinear wave signature of and oscillating and translating disturbance in two-layer fluid. *Journal of Fluid Mechanics,* **675**: 477–494.

24. Alam, M.-R., Liu, Y. and Yue, D.K.P. 2011b Attenuation of short surface waves by the sea floor via nonlinear sub-harmonic interaction. *Journal of Fluid Mechanics,* **689**: 529–540.

25. Lavos, S., Mei, C. C. & Liu, Y. 2010 Oscillating water column at a coastal corner for wavepower extraction. *Applied Ocean Research*, Vol. 32, No. 3, pp 267-283.

26. Alam, M.-R., Liu, Y. and Yue, D.K.P. 2010 Oblique sub- and super-harmonic Bragg resonance of surface waves by bottom ripples. *Journal of Fluid Mechanics,* **643**: 437-447

27. Yan, H., Liu, Y., Kominiarczuk, J. & Yue, D.K.P. 2009 Cavity dynamics in water entry at low Froude numbers. *Journal of Fluid Mechanics,* **641**: 441-461.

28. Alam, M.-R., Liu, Y. & Yue, D.K.P. 2009a Bragg resonance of waves in a two-layer fluid propagating over bottom ripples. Part I. Perturbation analysis. *Journal of Fluid Mechanics,* **624**: 191-224.

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31. Zhu, Q., Liu, Y. & Yue, D.K.P. 2008 Resonant interaction of Kelvin ship waves and ambient waves. *Journal of Fluid Mechanics,* **597**: 171-197.

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33. Zhu, Q., Liu, Y. & Yue, D.K.P. 2006 Dynamics of a three-dimensional oscillating foil near the free surface, AIAA Journal., vol. **44** no. **12**, 2997-3009.

34. Wu, G. Liu, Y. & Yue, D.K.P. 2006 A note on stabilizing the Benjamin-Feir instability, *Journal of Fluid Mechanics*, **556**: 45-54.

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38. Liu, Y., Xue, M. & Yue, D.K.P. 2001 Computations of fully-nonlinear three-dimensional wave-wave and wave-body interactions --- Part II: Nonlinear wave force and runup on a body. *Journal of Fluid Mechanics* **438**, 41-66.

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